HALE: A FAR-INFRARED POLARIMETER FOR SOFIA

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ABSTRACT

Hale will be proposed as the first multi-wavelength imaging polarimeter for far-infrared wavelengths. Observations of giant molecular clouds have shown well ordered magnetic fields and strongly varying polarization spectra. The sensitivity and resolution achievable with Hale on SOFIA will make it possible to observe other types of objects such as dark clouds, infrared cirrus, and external galaxies. These sources are expected to show contrasting polarization spectra corresponding to differences in their radiation fields, thermal properties, and dust populations.

Hale will have two detector arrays: one for each component of linear polarization. To the extent possible the arrays will fill SOFIA's useful focal plane with diffraction-limited detectors.

SCIENTIFIC POTENTIAL

The first far-infrared polarimetry on the Kuiper Airborne Observatory with the single-pixel instrument, Mark I, produced a polarization "map" of Orion with two 55 arcsec beams (Dragovan 1986). Mark I was later replaced by the 32-pixel polarimeters Stokes on the KAO (Platt et al. 1991) and Hertz on the CSO (Dowell et al. 1998). A polarization map of Orion made with Hertz is shown in Figure 1. Hale will have thousands of pixels and greatly improved sensitivity and angular resolution.

In Orion's core, Hale's resolution on SOFIA, 5 arcsec at 53 μm, will be sufficient to resolve polarization domains thus far observed only in a restricted region by millimeter-wave interferometry (Rao et al. 1998). Hale will map with comparable resolution over a much larger area, and because it will be sensitive to the warm dust in the core, it will discriminate against emission from cool foreground and background dust.

Comparisons of results from the KAO (60 μm and 100 μm), CSO (350μm) and JCMT (850 μm and 1300 μm) have shown a rapidly varying polarization spectrum in giant molecular clouds (Fig. 2A). We interpret this as an effect of differences in the environments of grains in various cloud components (Hildebrand et al. 1999; Vaillancourt 2002). We expect that diffuse Galactic emission from infrared cirrus will exhibit a polarization spectrum that is considerably simpler (Fig. 2B), because all the grains in these clouds should be exposed to the same radiation field. Hale will have the sensitivity to measure this polarization spectrum. The resulting models should enable cosmologists to better distinguish polarized emission from the early universe from that produced in the diffuse Galactic medium.

Figure 2B shows polarization spectra we have derived from a two-component dust model as inferred from COBE data by Finkbeiner, Davis, and Schlegel (1999). The three spectra shown (a, b, and c) correspond to different model parameters (see inset). The cooler component is referred to as A and the hotter as B. The relative peak intensities of the component spectra are denoted by FA

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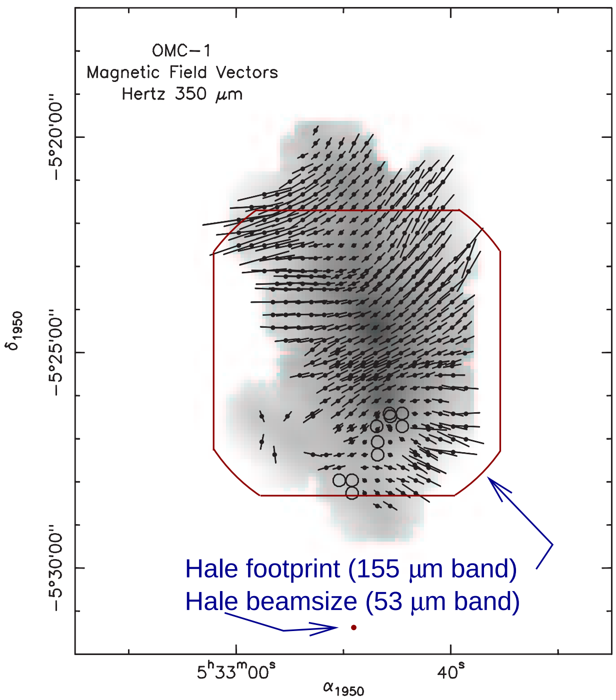

Figure 1: Polarization map of Orion, and capabilities of Hale/SOFIA.

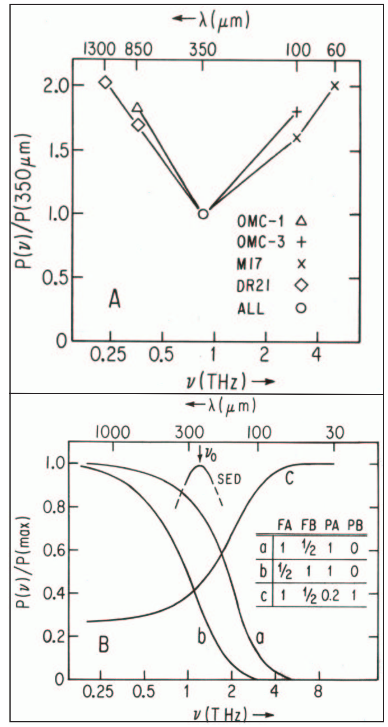

Figure 2: Polarization spectra: (A) as observed in molecular clouds, and (B) as predicted for diffuse Galactic emission, with three possibilities shown.

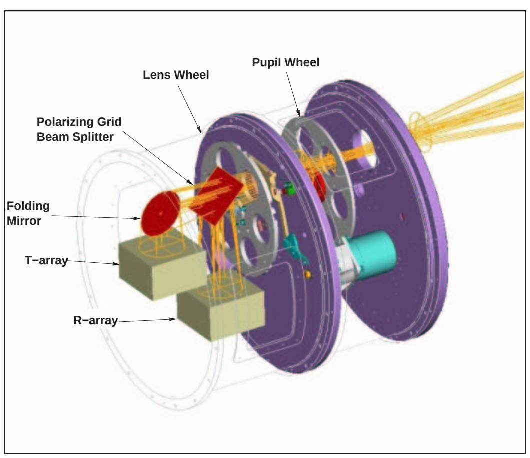

Figure 3: Optical design of Hale

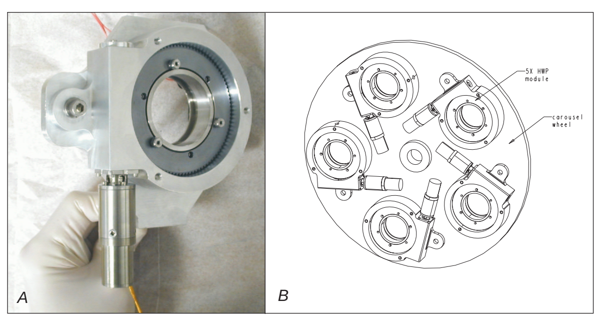

Figure 4: (A) Prototype half−wave plate module for Hale. (B) Hale's pupil carousel wheel with 5 half−wave plate modules

Table 1: *Hale Specifications*

Parameter	Band 1	Band 2	Band 3	Band 4
Central wavelength (μm)	53	88	155	215
Central frequency (THz)	5.7	3.4	1.9	1.4
Band width, FWHM ($\Delta\lambda/\lambda$)	0.10	0.10	0.14	0.20
Pixel size (arcsec)	2.25	3.5	6.0	8.0
Pixel solid angle (10^{-9} sr)	0.12	0.29	0.85	1.5
Field of view: 64×64 array (arcmin)	2.4×2.4	3.7×3.7	6.4×6.4	8.5×8.5
Resolution, 1.2 λ/D (arcsec)	5.2	8.6	15.2	21
Background power/pixel (pW)	13	12	14	10
NEFD (Jy s$^{-1/2}$)	2.0	1.3	1.2	0.7
$\sigma(P)$, 1 hr., 30 Jy source (%)	0.21	0.14	0.13	0.083
$\sigma(P)$, 10 hr., 1 Jy source (%)	2.1	1.4	1.3	0.79
$\sigma(\theta)$, 1 hr., 30 Jy source, $P = 3\%$	2°	1°	1°	1°
$\sigma(\theta)$, 10 hr., 1 Jy source, $P = 3\%$	20°	13°	14°	7°

and FB, and the relative polarization efficiencies by PA and PB. Also shown in the figure is the total flux spectrum (SED). The three model polarization spectra can be differentiated on the basis of the sign of the slope, and the location of the point of inflection relative to the peak of the SED. Although the temperature difference (6 K) between A and B is the same for the three models shown, the polarization spectrum can in fact also be used as an independent probe of this parameter. Hale will provide the only access to the high frequency side of the polarization spectrum of cirrus clouds.

INSTRUMENT DESIGN

The specifications of Hale are given in Table 1. For many of Hale's components, costs will be substantially reduced by using designs that have been developed for HAWC, the SOFIA facility photometer now under construction (Harper et al. 2000). For example, we plan to use the cryostat design of HAWC. Also, the spectral passbands will be the same as those for HAWC. In addition to permitting diffraction-limited polarimetric imaging in each of the four HAWC passbands, Hale will have a fifth "band" (not shown in the table) that could be used for another wavelength or for reduced magnification in cases where large area coverage is more important than diffraction-limited resolution.

Our plan for the Hale optical system is shown in Figure 3. Note the light rays entering the instrument at upper right. Principal components of the optical system are: fore optics (not shown) that produce an image of the primary near the cold side of the dewar window; two carousel wheels that permit switching between the five bands while the instrument is cold (the wheels hold lenses, filters, and half-wave plates); a polarizing grid beamsplitter; and two detector arrays, one for each of two orthogonal components of linear polarization. We plan to use an adiabatic demagnetization refrigerator similar to that designed for HAWC to cool the detector arrays. The remainder of the optics shown in Figure 3 will be cooled to 4 K. The fore optics are similar to those used by HAWC, consisting of ambient temperature mirrors.

We have successfully tested a prototype module in which a half-wave plate is driven by a cryogenic motor (Fig. 4; Rennick et al. 2002). Five such modules will be mounted to Hale's pupil carousel wheel (Fig. 4B).

A goal is to come as close as possible to filling the focal plane with diffraction-limited and background-limited detectors. This conference should serve as a guide to the array size that can realistically be proposed for an instrument to be built beginning in about 2005. In Table 1 we give the field of view for each passband, assuming a 64 x 64 array with pixels of size $\lambda/2D$. This should be compared with the 8 arcminute diameter field of view of the SOFIA telescope. In developing the optical design shown in Figure 3, we assumed that the physical size of each pixel is 1 mm $\times$ 1 mm, and we allowed a volume of 5 $\times$ 5 $\times$ 3 inches for each detector array.

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